

# LEPTOQUARK PRODUCTION IN $e^-e^-$ SCATTERING

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## Abstract

We consider the production of scalar and vector leptoquarks in  $e^-e^-$  collisions. Although this reaction is not competitive with *e.g.*  $e^-\gamma$  scattering for discovering these heavy states, it is the main process susceptible of differentiating two important classes of leptoquarks.

Leptoquarks appear in a wealth of extensions of the standard model, ranging from grand unified to composite models. A general classification of these states which respects  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  invariance was performed in Ref. [1]. It assumes that:

- By definition, they couple to leptons and quarks. Therefore, they must be either singlets, doublets or triplets of the weak gauge group  $SU(2)_L$ .
- For simplicity, their couplings to leptons and quarks do not involve derivatives. This ensures only lowest dimension operators are involved.
- In order not to induce rapid proton decay or other nuisances, they must conserve lepton ( $L$ ) and baryon ( $B$ ) number separately.

The most general effective lagrangian which respects these conditions reads [1]

$$\begin{aligned}
 L = & (h_{2L}\bar{u}_R\ell_L + h_{2R}\bar{q}_L i\sigma_2 e_R)R_2 + \tilde{h}_{2L}\bar{d}_R\ell_L\tilde{R}_2 + h_{3L}\bar{q}_L\boldsymbol{\sigma}\gamma^\mu\ell_L\mathbf{U}_{3\mu} \\
 & + (h_{1L}\bar{q}_L\gamma^\mu\ell_L + h_{1R}\bar{d}_R\gamma^\mu e_R)U_{1\mu} + \tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} \\
 & + (g_{1L}\bar{q}_L^c i\sigma_2\ell_L + g_{1R}\bar{u}_R^c e_R)S_1 + \tilde{g}_{1R}\bar{d}_R^c e_R\tilde{S}_1 + g_{3L}\bar{q}_L^c i\sigma_2\boldsymbol{\sigma}\ell_L\mathbf{S}_3 \\
 & + (g_{2L}\bar{d}_R^c\gamma^\mu\ell_L + g_{2R}\bar{q}_L^c\gamma^\mu e_R)V_{2\mu} + \tilde{g}_{2L}\bar{u}_R^c\gamma^\mu\ell_L\tilde{V}_{2\mu} + \text{h.c.} ,
 \end{aligned} \tag{1}$$

where the  $\boldsymbol{\sigma}$ 's are Pauli matrices, while  $q_L$  and  $\ell_L$  are the  $SU(2)_L$  quark and lepton doublets and  $u_R$ ,  $d_R$ ,  $\ell_R$  are the corresponding singlets. The subscripts of the

leptoquarks indicates the size of the  $SU(2)_L$  representation they belong to. The  $R$ - and  $S$ -type leptoquarks are spacetime scalars, whereas the  $U$  and  $V$  are vectors. All leptoquarks carry a fermion number  $F = 3B + L = 0, 2$  and family and colour indices are implicit. These quantum numbers are summarized in Table 1.

|               | $J$ | $F$ | $T$   | $T_3$           | $Q$                       | couples to  |
|---------------|-----|-----|-------|-----------------|---------------------------|---|
| $S_1$         | 0   | 2   | 0     | 0               | $-1/3$                    | $e_L u_L \quad e_R u_R \quad \nu_L d_L$                                       |
| $\tilde{S}_1$ | 0   | 2   | 0     | 0               | $-4/3$                    | $e_R d_R$   |
| $R_2$         | 0   | 0   | $1/2$ | $-1/2$<br>$1/2$ | $-5/3$<br>$-2/3$          | $e_R \bar{u}_L \quad e_L \bar{u}_R$<br>$e_R \bar{d}_L \quad \nu_L \bar{u}_R$  |
| $\tilde{R}_2$ | 0   | 0   | $1/2$ | $-1/2$<br>$1/2$ | $-2/3$<br>$1/3$           | $e_L \bar{d}_R$<br>$\nu_L \bar{d}_R$  |
| $S_3$         | 0   | 2   | 1     | $-1$<br>0<br>1  | $-4/3$<br>$-1/3$<br>$2/3$ | $e_L d_L$<br>$e_L u_L \quad \nu_L d_L$<br>$\nu_L u_L$                         |
| $U_1$         | 1   | 0   | 0     | 0               | $-2/3$                    | $e_L \bar{d}_L \quad e_R \bar{d}_R \quad \nu_L \bar{u}_L$                     |
| $\tilde{U}_1$ | 1   | 0   | 0     | 0               | $-5/3$                    | $e_R \bar{u}_R$   |
| $V_2$         | 1   | 2   | $1/2$ | $-1/2$<br>$1/2$ | $-4/3$<br>$-1/3$          | $e_R d_L \quad e_L d_R$<br>$e_R u_L \quad \nu_L d_R$                          |
| $\tilde{V}_2$ | 1   | 2   | $1/2$ | $-1/2$<br>$1/2$ | $-1/3$<br>$2/3$           | $e_L u_R$<br>$\nu_L u_R$  |
| $U_3$         | 1   | 0   | 1     | $-1$<br>0<br>1  | $-5/3$<br>$-2/3$<br>$1/3$ | $e_L \bar{u}_L$<br>$e_L \bar{d}_L \quad \nu_L \bar{u}_L$<br>$\nu_L \bar{d}_L$ |

Table 1: Main quantum numbers of the leptoquarks.

The best present bounds on leptoquarks still originate from low energy experiments [2], and the constraints on flavour diagonal couplings are weak, at best. Some improvement is expected from HERA [1], but the real breakthrough should be obtained in high energy experiments of the next generation [3, 4]. A particularly promising option is a linear collider operated in the  $e^- \gamma$  mode [5], where single leptoquarks can be produced and very well studied.

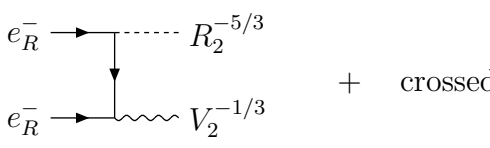
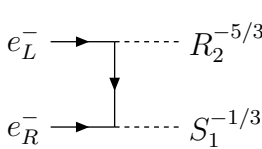
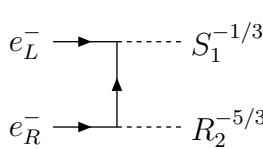
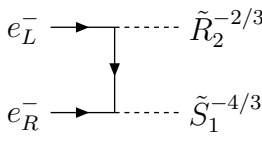
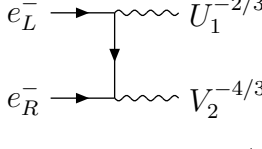
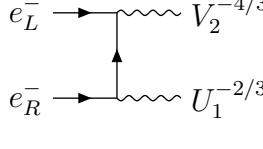
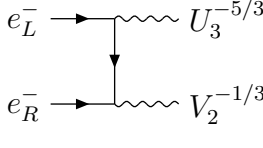
|           | $F = 0$                   | $F = 2$  |  |
|-----------|---------------------------|--|--|
| <b>1:</b> | $e_R^- e_R^- \rightarrow$ | $\left  \begin{array}{l} R_2^{-5/3} \\ R_2^{-2/3} \\ \tilde{U}_1^{-5/3} \\ U_1^{-2/3} \end{array} \right.$ | $\left  \begin{array}{l} V_2^{-1/3} \\ V_2^{-4/3} \\ S_1^{-1/3} \\ \tilde{S}_1^{-4/3} \end{array} \right.$                             |
|           | $e_L^- e_L^- \rightarrow$ | $\left  \begin{array}{l} R_2^{-5/3} \\ R_2^{-2/3} \\ U_3^{-5/3} \\ U_3^{-2/3} \end{array} \right.$         | $\left  \begin{array}{l} \tilde{V}_2^{-1/3} \\ V_2^{-4/3} \\ S_1^{-1/3} \\ S_3^{-1/3} \\ S_3^{-4/3} \\ S_3^{-4/3} \end{array} \right.$ |
|           |                           |  |    |
| <b>2:</b> | $e_L^- e_R^- \rightarrow$ | $R_2^{-5/3}$   | $S_1^{-1/3}$   |
|           |                           |                         |    |
| <b>3:</b> | $e_L^- e_R^- \rightarrow$ | $\left  \begin{array}{l} \tilde{R}_2^{-2/3} \\ R_2^{-5/3} \\ R_2^{-2/3} \end{array} \right.$               | $\left  \begin{array}{l} \tilde{S}_1^{-4/3} \\ S_3^{-1/3} \\ S_3^{-4/3} \end{array} \right.$   |
|           |                           |                        |  |
| <b>4:</b> | $e_L^- e_R^- \rightarrow$ | $U_1^{-2/3}$   | $V_2^{-4/3}$   |
|           |                           |                        |   |
| <b>5:</b> | $e_L^- e_R^- \rightarrow$ | $\left  \begin{array}{l} U_3^{-5/3} \\ U_3^{-2/3} \\ \tilde{U}_1^{-5/3} \end{array} \right.$               | $\left  \begin{array}{l} V_2^{-1/3} \\ V_2^{-4/3} \\ \tilde{V}_2^{-1/3} \end{array} \right.$   |
|           |                           |                        |  |

Figure 1: Leptoquark production processes and their typical Feynman diagrams.

Leptoquark production in  $e^-e^-$  scattering [6] is a possibility which at first sight is not particularly attractive. Indeed, two leptoquarks have to be produced in this process, making it inadequate for discovering these particles if they are heavy. Electron-photon [5], electron-proton [1] or proton-proton [4] reactions are much better suited for this. Moreover, the  $e^-e^-$  cross sections involve the fourth power of the couplings to electrons and quarks, which are totally unknown and might well be small. In contrast, in  $e^+e^-$  annihilation [3] or photon-gluon fusion [7], the cross sections mainly depend on the mass and the charge of the produced leptoquarks and are always large above threshold.

There is, however, one quantum number that only one of the other experiments is able to measure well: the fermion number  $F$ . As it turns out, no standard reaction can see a large difference between  $F = 0$  and  $F = 2$  leptoquarks, except electron-(anti)quark fusion [1] which can only take place via  $(F = 0) F = 2$  leptoquarks, and  $e^-e^-$  scattering which can only take place if both kinds are present. Unfortunately, HERA can only probe light leptoquarks and this situation is not going to improve unless LEP-LHC is ever turned on. This is why the  $e^-e^-$  operating mode can play an important role in leptoquark searches: if a reaction takes place, we know for sure that we have produced one  $F = 0$  and one  $F = 2$  leptoquark.

According to the lagrangian (1), there are five possible types of reactions, which we list in Fig. 1. Their total cross sections are

$$\sigma_1 = 4G \left[ S + L \left( D + 2m_S^2 + 2\frac{m_S^4}{D} \right) \right] \quad (2)$$

$$\sigma_2 = 2G \left[ 3S + L \left( D + 2\frac{m_0^2 m_2^2}{D} \right) \right] \quad (3)$$

$$\sigma_3 = G [ 2S + LD ] \quad (4)$$

$$\sigma_4 = 8G \left[ 2S + L \left( D + 2(m_0^2 + m_2^2) + 2\frac{(m_0^2 + m_2^2)^2}{D} \right) \right] \quad (5)$$

$$\sigma_5 = G \left[ \frac{S}{6} \left( \frac{D^2}{m_0^2 m_2^2} + 12 \left( \frac{D}{m_0^2} + \frac{D}{m_2^2} \right) + 12 \left( \frac{m_0^2}{m_2^2} + \frac{m_2^2}{m_0^2} \right) - 28 \right) - 4LD \right] \quad (6)$$

where

$$\left\{ \begin{array}{l} G = \frac{3\pi\alpha^2}{s^2} \left( \frac{\lambda}{e} \right)^4 \\ D = s - m_0^2 - m_2^2 \\ S = \sqrt{D^2 - 4m_0^2 m_2^2} \\ L = \ln \frac{D+S}{D-S} \end{array} \right\} \quad \left\{ \begin{array}{l} \lambda^2 = hg = \text{leptoquark-lepton-quark couplings} \\ m_0 = \text{mass of the } F = 0 \text{ leptoquark} \\ m_2 = \text{mass of the } F = 2 \text{ leptoquark} \\ m_S = \text{mass of the scalar leptoquark} \end{array} \right. \quad (7)$$

The energy and mass dependence of these cross sections are displayed in Figs 2 and 3, assuming

- 100% polarized beams,
- both leptoquarks have the same common mass  $m_{LQ}$  and

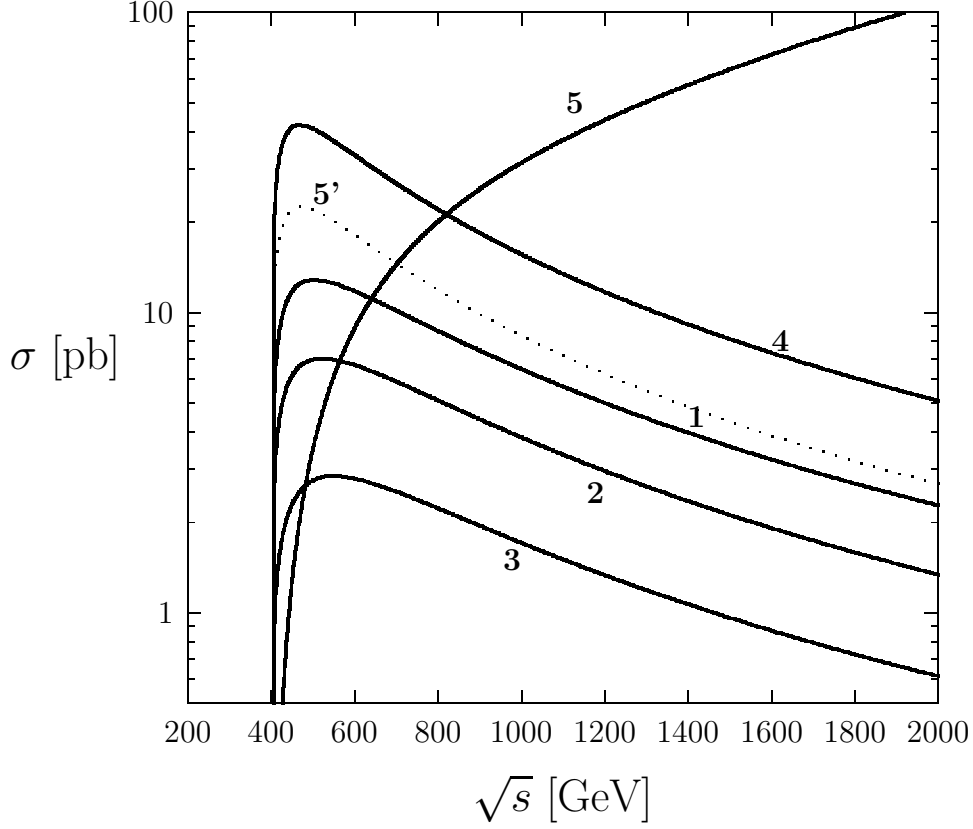


Figure 2: Cross section as a function of the collider energy. The mass of the produced leptoquarks is 200 GeV.

- they couple to the electron and quark with the generic coupling  $\lambda^2 = hg = e^2$ . This is not realistic, but may serve as a benchmark.

The high energy and threshold behaviours of these cross sections are the following:

$$\begin{aligned}
 s \gg m_0^2, m_2^2 : & \left\{ \begin{array}{ll} \sigma_{1-4} & \propto \frac{1}{s} \ln \frac{s}{m_0 m_2} \\ \sigma_5 & \propto s \end{array} \right. \\
 s \approx (m_0 + m_2)^2 : & \left\{ \begin{array}{ll} \sigma_{1-4} & \propto \sqrt{s - (m_0 + m_2)^2} \\ \sigma_5 & \propto s - (m_0 + m_2)^2 \end{array} \right.
 \end{aligned} \tag{8}$$

The pathological breaking of perturbative unitarity in the process **5** is due to its purely  $t$ -channel nature. A similar situation is also encountered in  $e^+e^-$  scattering [3]. There are two possible cures to this:

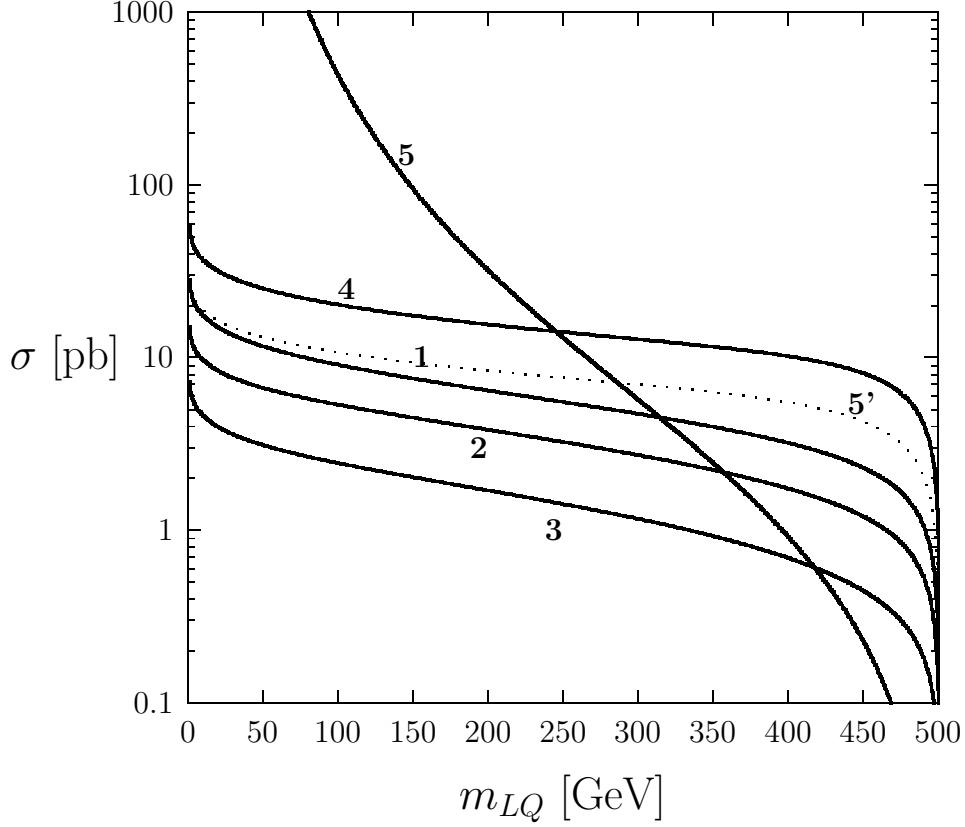


Figure 3: Cross section as a function of the mass of the produced leptoquarks. The collider energy is 1 TeV.

- For non-gauge leptoquarks, one anyway expects other new physics effects to set in at some higher energy scale.
- For gauge leptoquarks, though, one may also expect a dilepton to be exchanged in the  $s$ -channel, as shown in Fig. 4. If this is the case, the cross section becomes well behaved as in reactions **1**–**4**. It is represented by the dotted curves in Figs. 2 and 3, with the dilepton mass set equal to the common leptoquark mass. We number this type of reaction **5'**. Its cross section is

$$\begin{aligned}
 \sigma_{5'} = & G \left\{ \frac{S}{6} \left[ 62 + \frac{2m_D^2 - m_0^2}{m_2^2} + \frac{2m_D^2 - m_2^2}{m_0^2} - \frac{m_D^4}{m_0^2 m_2^2} \right. \right. \\
 & + \frac{2}{s - m_D^2} \left( 5m_0^2 + 5m_2^2 + 22m_D^2 - \frac{m_D^6}{m_0^2 m_2^2} \right. \\
 & \left. \left. + \frac{9m_0^2 m_D^2 - 5m_0^4 - 3m_D^4}{m_2^2} + \frac{9m_2^2 m_D^2 - 5m_2^4 - 3m_D^4}{m_0^2} \right) \right\} \quad (9)
 \end{aligned}$$

$$\begin{aligned}
& - \frac{1}{(s - m_D^2)^2} \left( 8m_0^4 + 8m_2^4 - 32m_D^4 - 32m_0^2 m_D^2 - 32m_2^2 m_D^2 - 18m_0^2 m_2^2 + \frac{m_D^8}{m_0^2 m_2^2} \right. \\
& \quad \left. + \frac{8m_0^4 m_D^2 - 18m_0^2 m_D^4 + m_0^6 + 8m_D^6}{m_2^2} + \frac{8m_2^4 m_D^2 - 18m_2^2 m_D^4 + m_2^6 + 8m_D^6}{m_0^2} \right) \\
& + 4L \left[ D + 2(m_0^2 + m_2^2) + 2 \frac{m_0^2 m_2^2 + m_2^2 m_D^2 + m_D^2 m_0^2}{s - m_D^2} \right] \Bigg\}
\end{aligned}$$

The leptoquarks produced in the processes **1–5'** decay with a substantial branching ratio into a charged lepton and a jet [3]. If the leptoquarks are family diagonal (*i.e.*, they couple to only one and the same generation of quarks and leptons), the decay lepton is an electron. Close to threshold, the signature is thus two high transverse momentum electrons-quark pairs and no missing energy. If we cut out the (very few) jet pairs with an invariant mass around the  $Z^0$  [8], the only background left over originates from the tiny quark photoproduction  $e^-e^- \rightarrow e^-e^-q\bar{q}$ . These events will also be removed by requiring the invariant masses of the electron-quark pairs to be centered around the leptoquarks' masses. If the leptoquarks mix different families, there can be a muon instead of an electron. In this case, of course, there is no background at all.

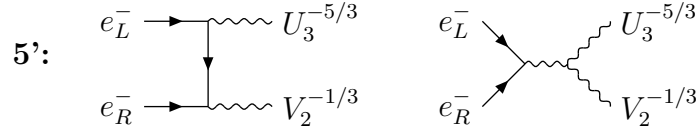


Figure 4: Typical Feynman diagrams involving the  $s$ -channel exchange of a dilepton.

To estimate the discovery potential, we have plotted in Fig. 5 the boundary in the  $(m_{LQ}, \lambda/e)$  plane, below which less than 10 events are observed in reaction **4**. For this we consider 5 different collider energies and assume  $10 \text{ fb}^{-1}$  of accumulated luminosity. Again the produced leptoquarks have the same mass. In general, the osculating curve is approximately given by

$$\frac{\lambda}{e} = 0.35 \sqrt{m_{LQ}/\text{TeV}} \left( \frac{n}{A \mathcal{L}/\text{fb}^{-1}} \right)^{1/4} \quad m_{LQ} \leq .43\sqrt{s} \ , \quad (10)$$

where  $\lambda = \sqrt{hg}$  is the geometric mean of the leptoquarks' couplings,  $m_{LQ}$  is their common mass,  $n$  is the required number of events,  $\mathcal{L}$  is the available luminosity and  $A = 6, 3, 1, 24, 12$  for reactions **1, 2, 3, 4, 5'** respectively.

To summarize, we have studied leptoquark production in the  $e^-e^-$  mode of a linear collider of the next generation. To perform this analysis, we have considered all types of scalar and vector leptoquarks, whose interactions with leptons and quarks

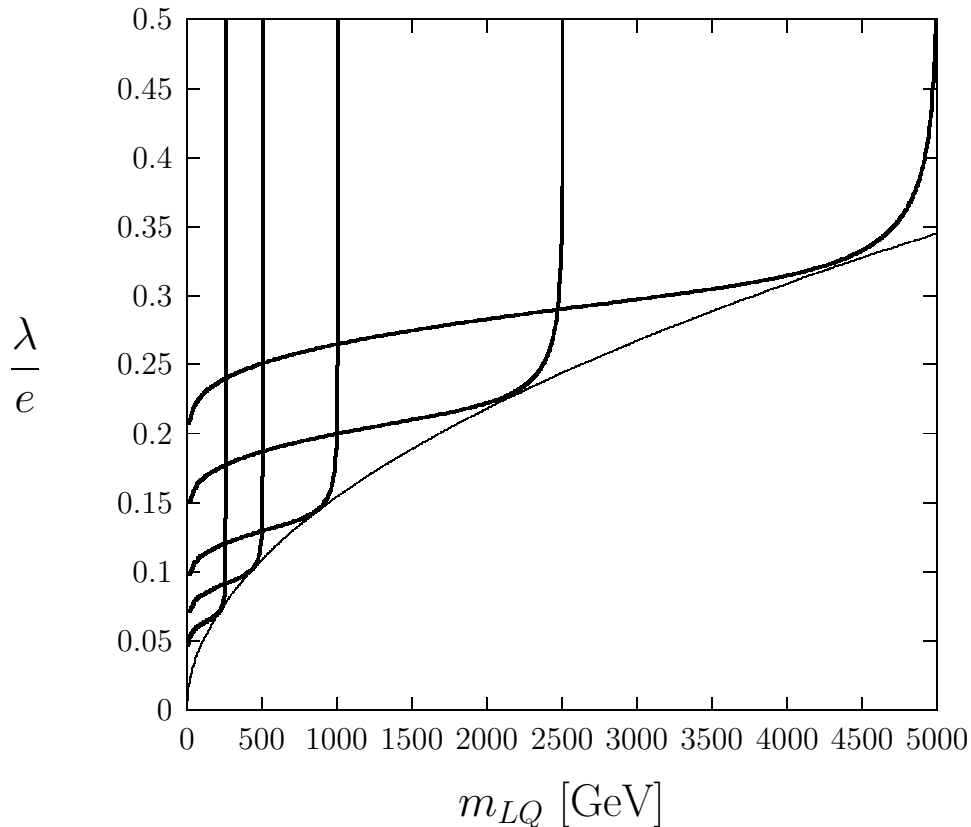


Figure 5: Loci of  $\sigma_4 = 1$  fb, as a function of the leptoquark mass and coupling to fermions. The collider energies are .5, 1, 2, 5 and 10 TeV. The thinner osculating parabola is given by Eq. (10).

conserve lepton and baryon number and are invariant under the standard model  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  gauge group. The standard model backgrounds can be reduced to almost zero by simple kinematical cuts, and the discovery potential is conveniently summarized by the scaling relation Eq. (10).

The  $e^-e^-$  leptoquark production processes are particularly interesting, because to lowest order they can only produce a pair of leptoquarks, one with fermion number  $F = 0$  and the other with  $F = 2$ . Therefore, the observation of such events would demonstrate the simultaneous existence of these two states. Similarly, the non-observation of this mechanism would impose strong bounds on extensions of the standard model. Except for electron-(anti)proton collisions, the other standard experiments are very weakly sensitive to this quantum number.

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